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Matsuda

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(54) **DEMULTIPLEXER AND DEMULTIPLEXER-RECEIVER**

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(52) **U.S. Cl.** **385/24**; 385/15; 385/18; 385/14; 385/37; 385/130; 385/131; 372/50; 372/96; 372/97; 372/99; 359/115; 359/124; 359/130

(58) **Field of Search** 385/24, 15, 27, 385/33, 35, 39, 129, 130, 131, 14; 372/23, 44, 45, 46, 50, 96, 97, 99, 101; 359/115, 124, 130

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,701,012 A	*	10/1987	Kaiser	385/37
4,923,271 A	*	5/1990	Henry et al.	385/37
5,029,176 A		7/1991	Chang-Hasnain	372/50
5,073,041 A	*	12/1991	Rastani	385/33
5,724,376 A	*	3/1998	Kish, Jr. et al.	372/96
5,835,517 A	*	11/1998	Jayaraman et al.	372/50
6,122,417 A	*	9/2000	Jayaraman et al.	385/24
6,212,312 B1	*	4/2001	Grann et al.	385/24

FOREIGN PATENT DOCUMENTS

JP	08-046593	2/1996	372/50 X

* cited by examiner

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(57) **ABSTRACT**

A demultiplexer according to the present invention includes a photonic crystalline layer, which is formed on the principal surface of a semiconductor substrate and transmits an incoming light beam with a predetermined wavelength. A wavelength at an edge of a photonic band of the photonic crystalline layer changes in a direction parallel to the principal surface of the substrate.

17 Claims, 7 Drawing Sheets

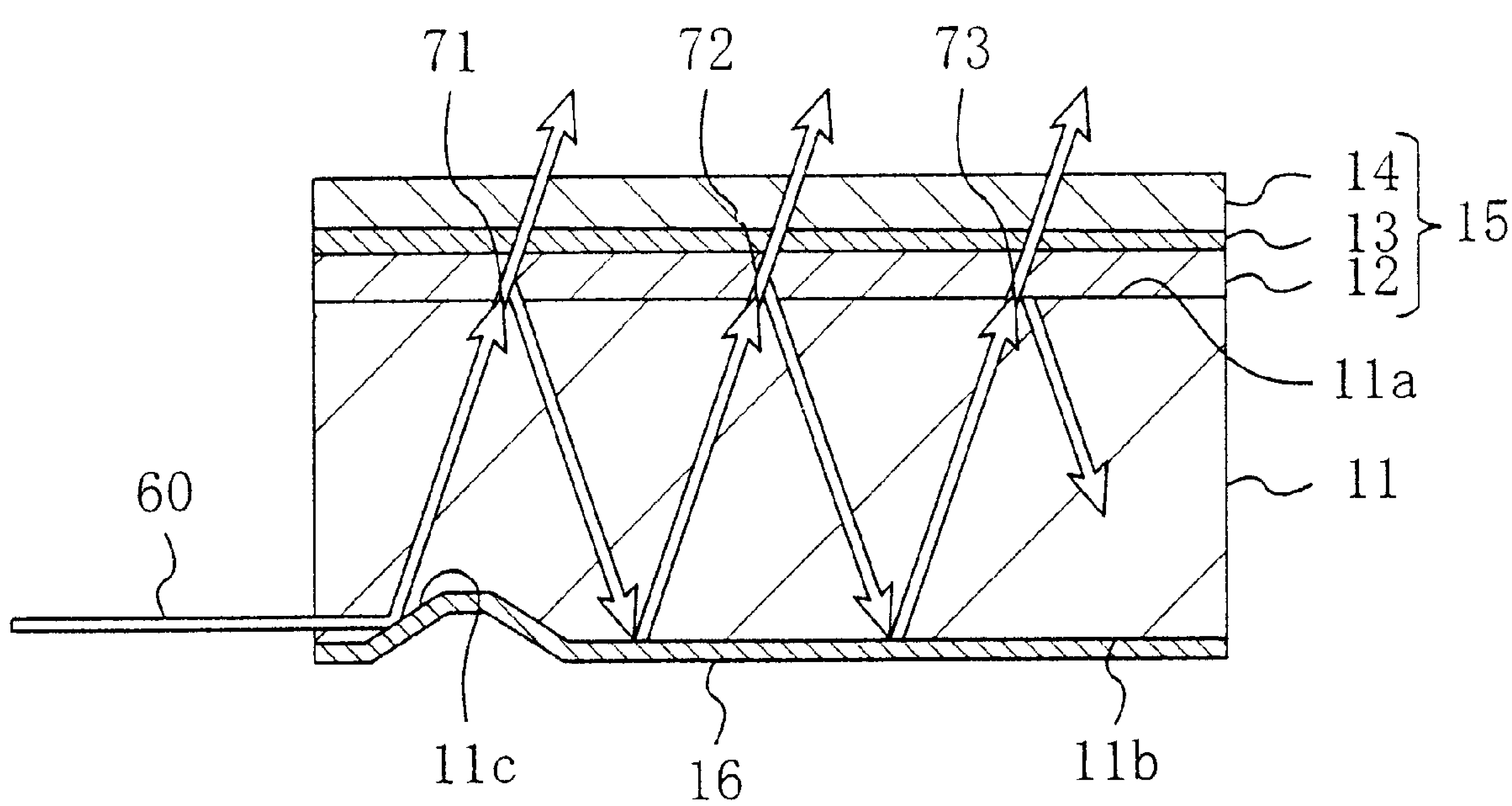


FIG. 1

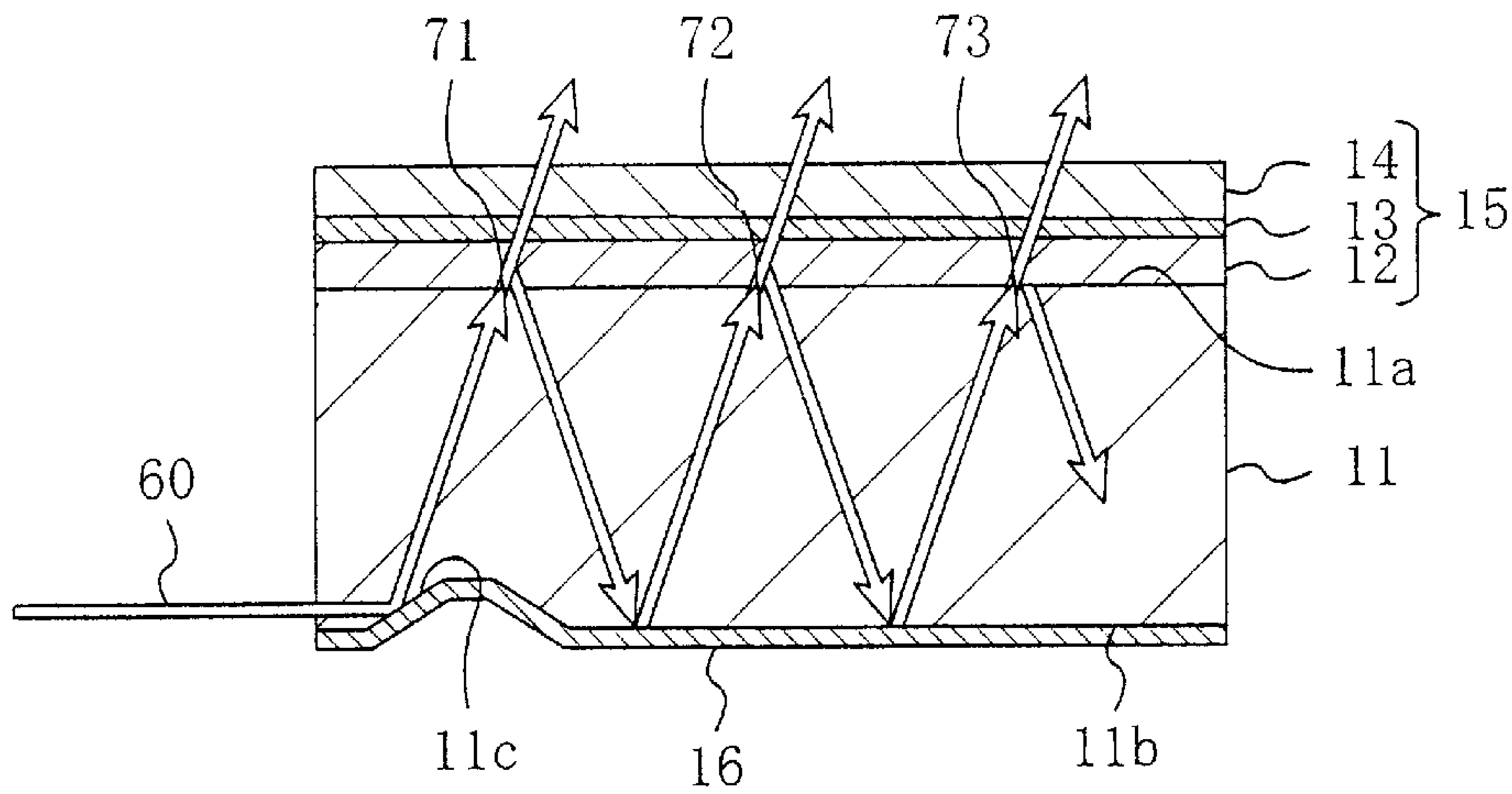
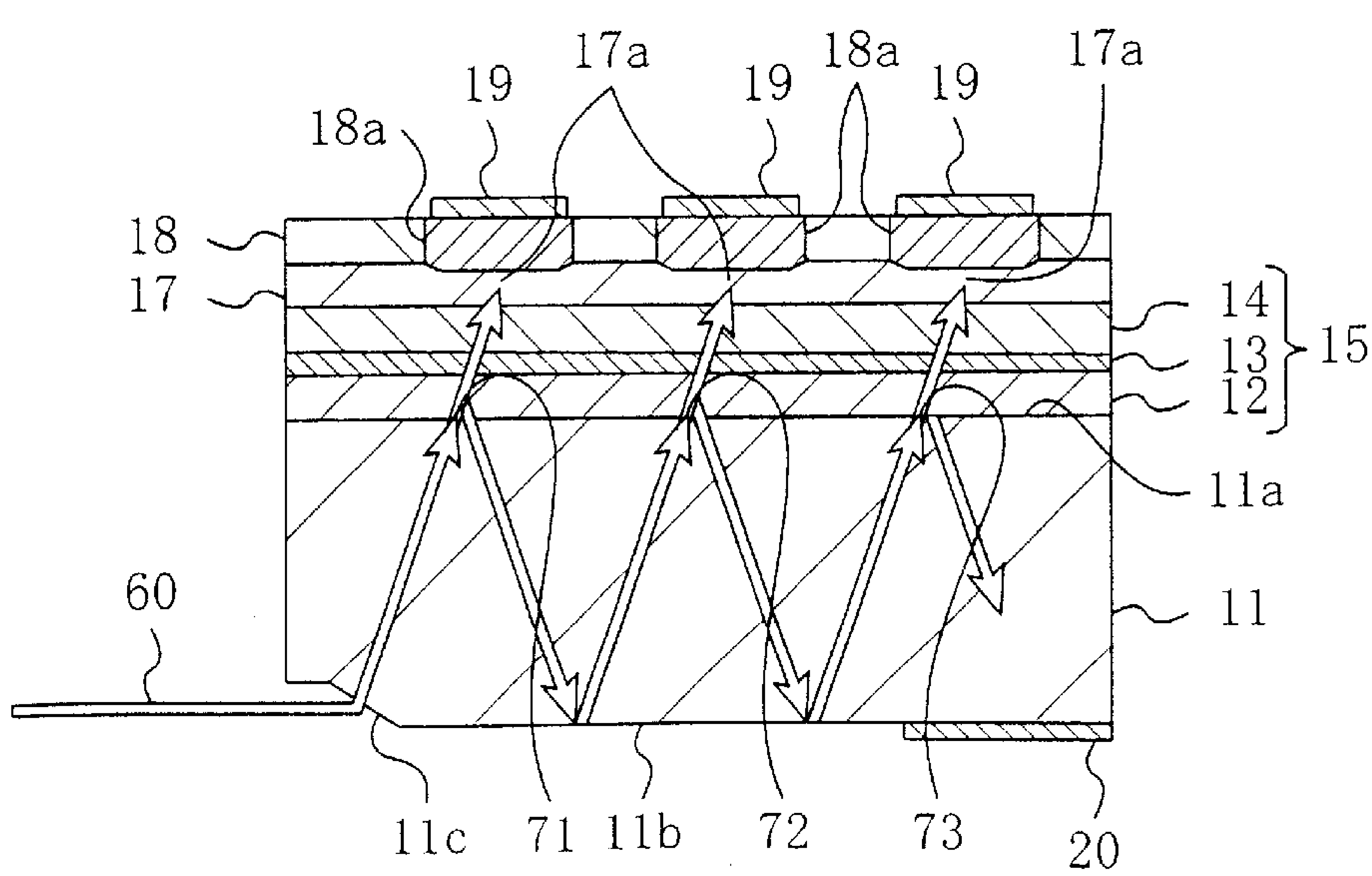

71
72
73
14
13
12
15
11a
60
11
11c
16
11b

FIG. 2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17a
18a
19
19
17a
18a
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11b
72
73
20

FIG. 3

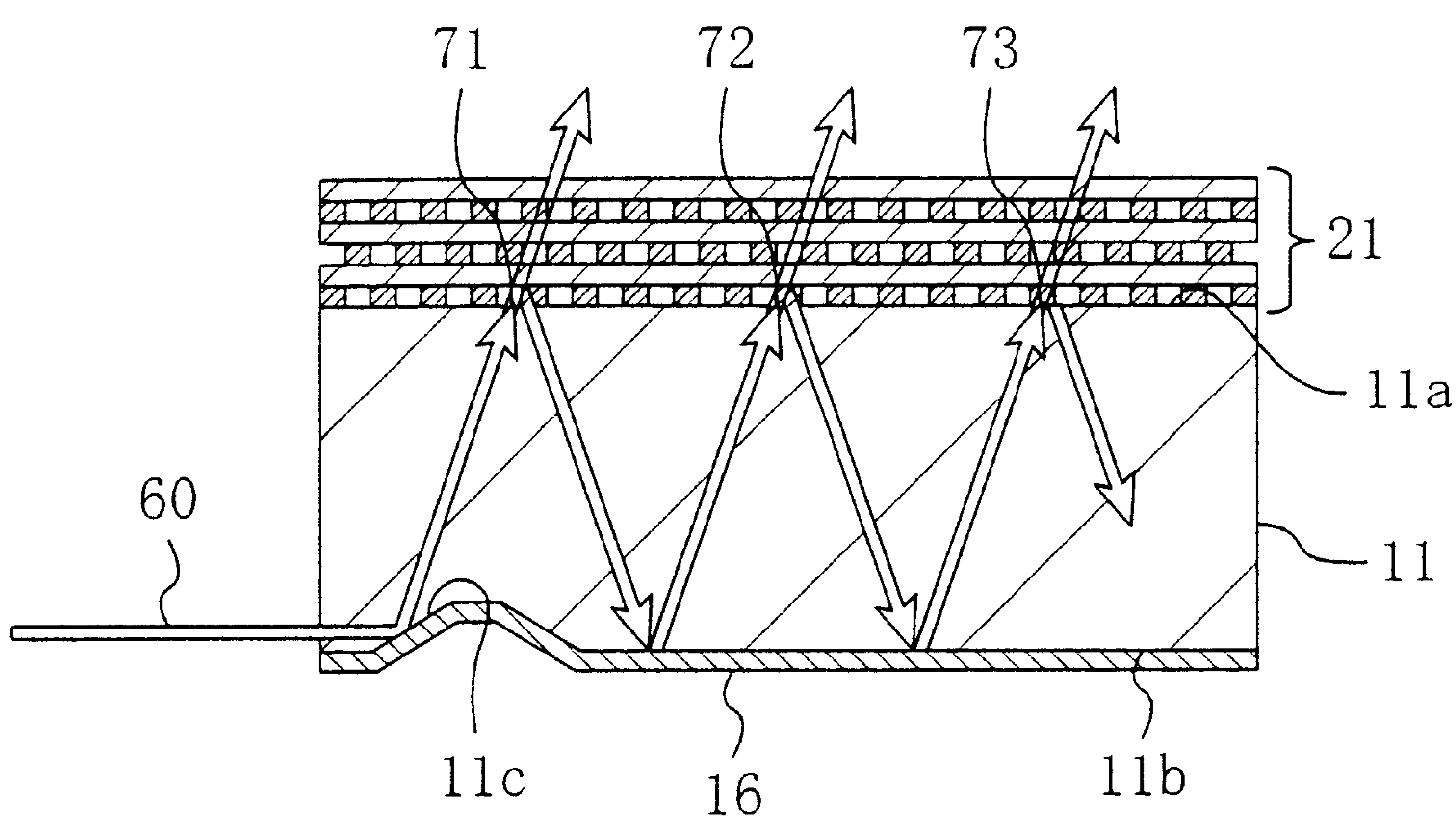


FIG. 4A

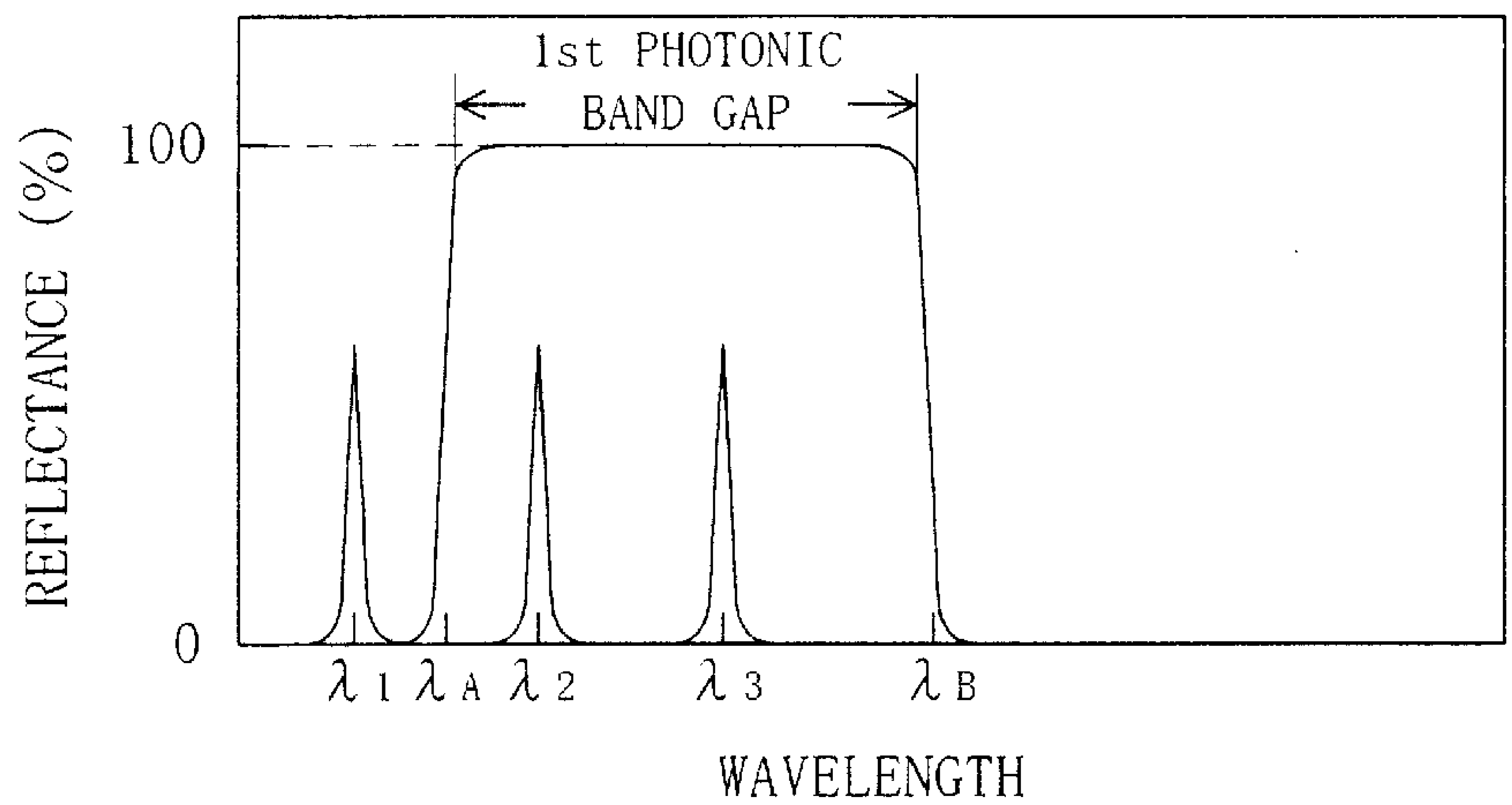


FIG. 4B

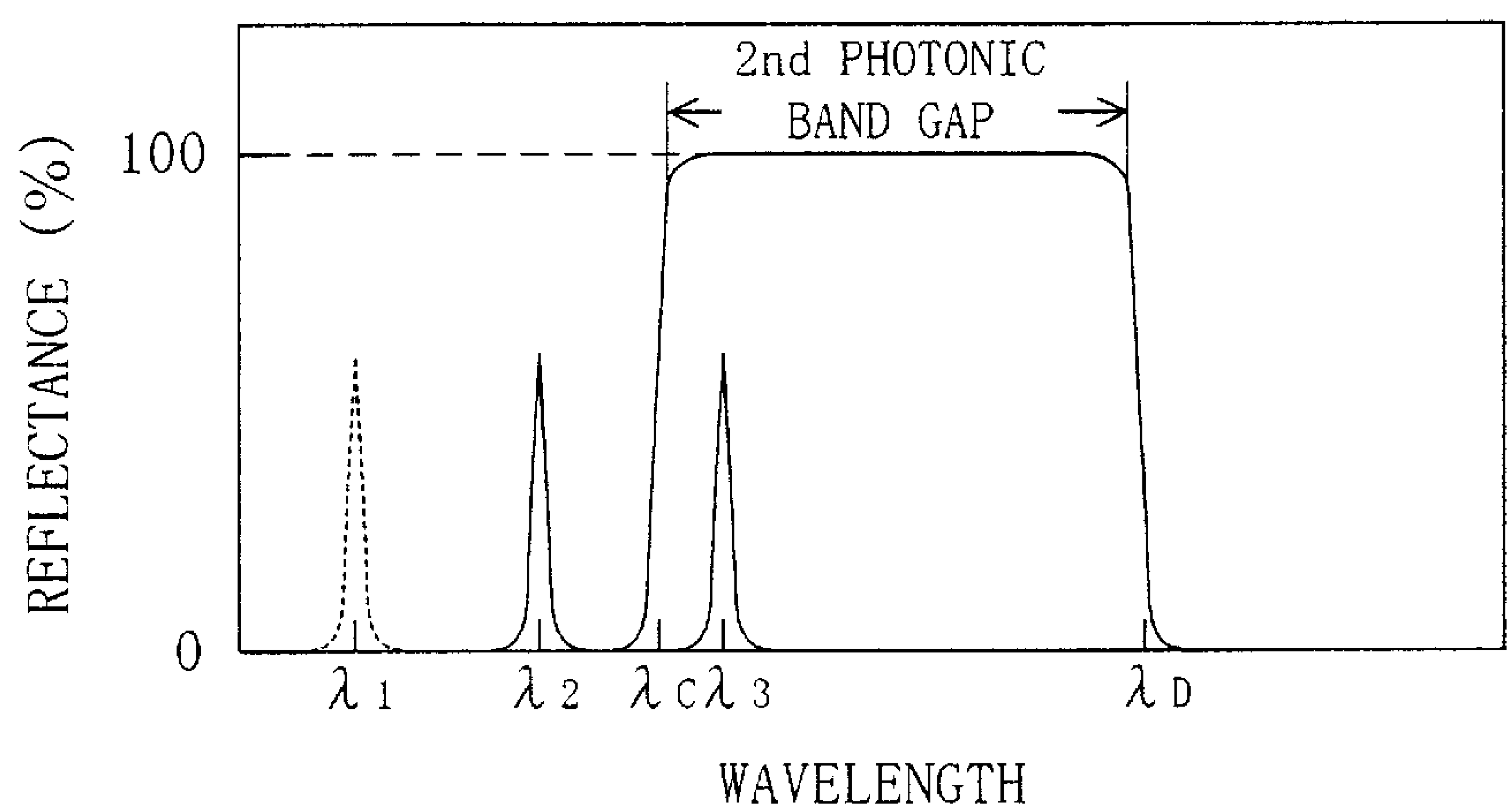


FIG. 4C

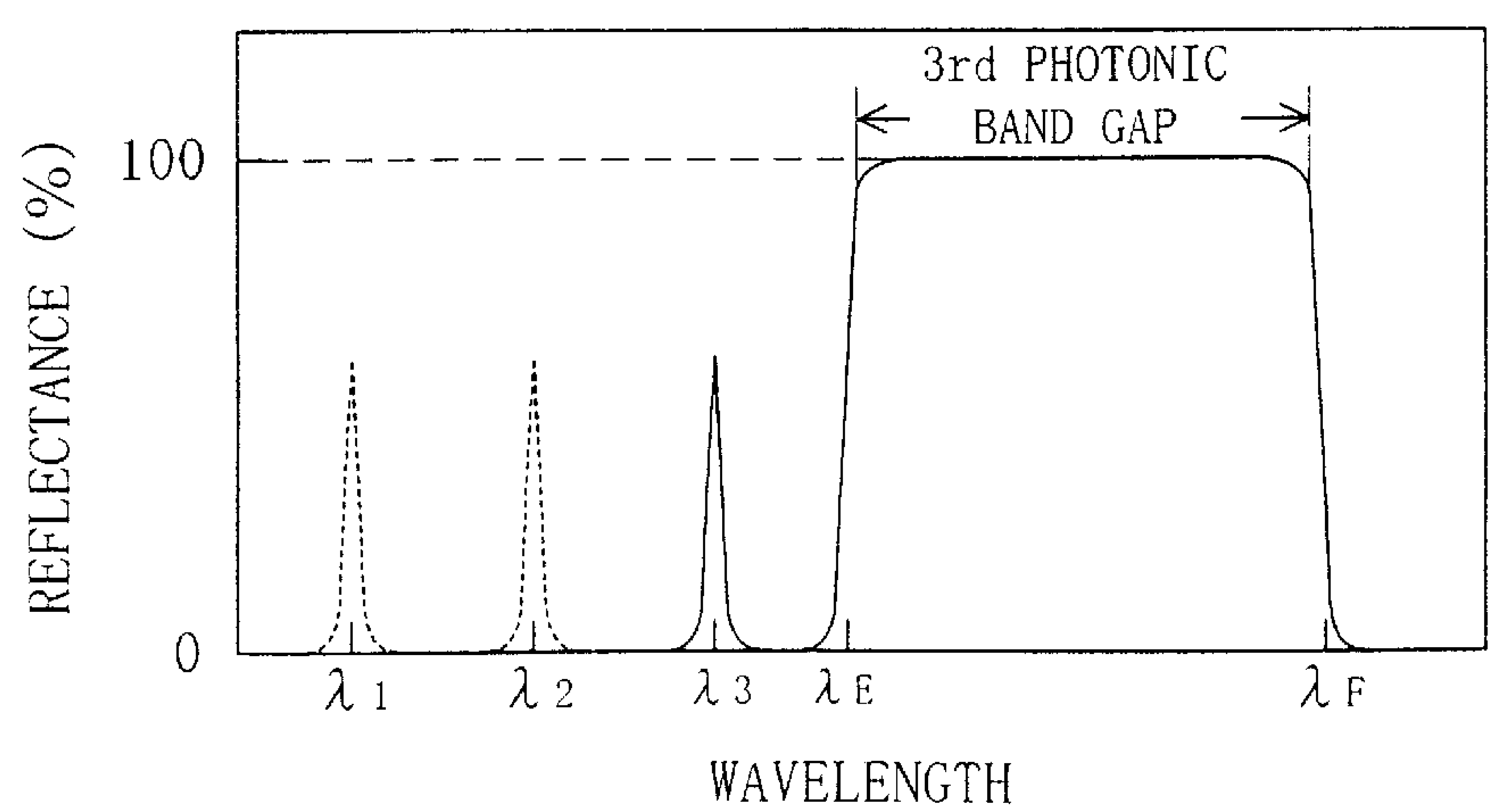


FIG. 5

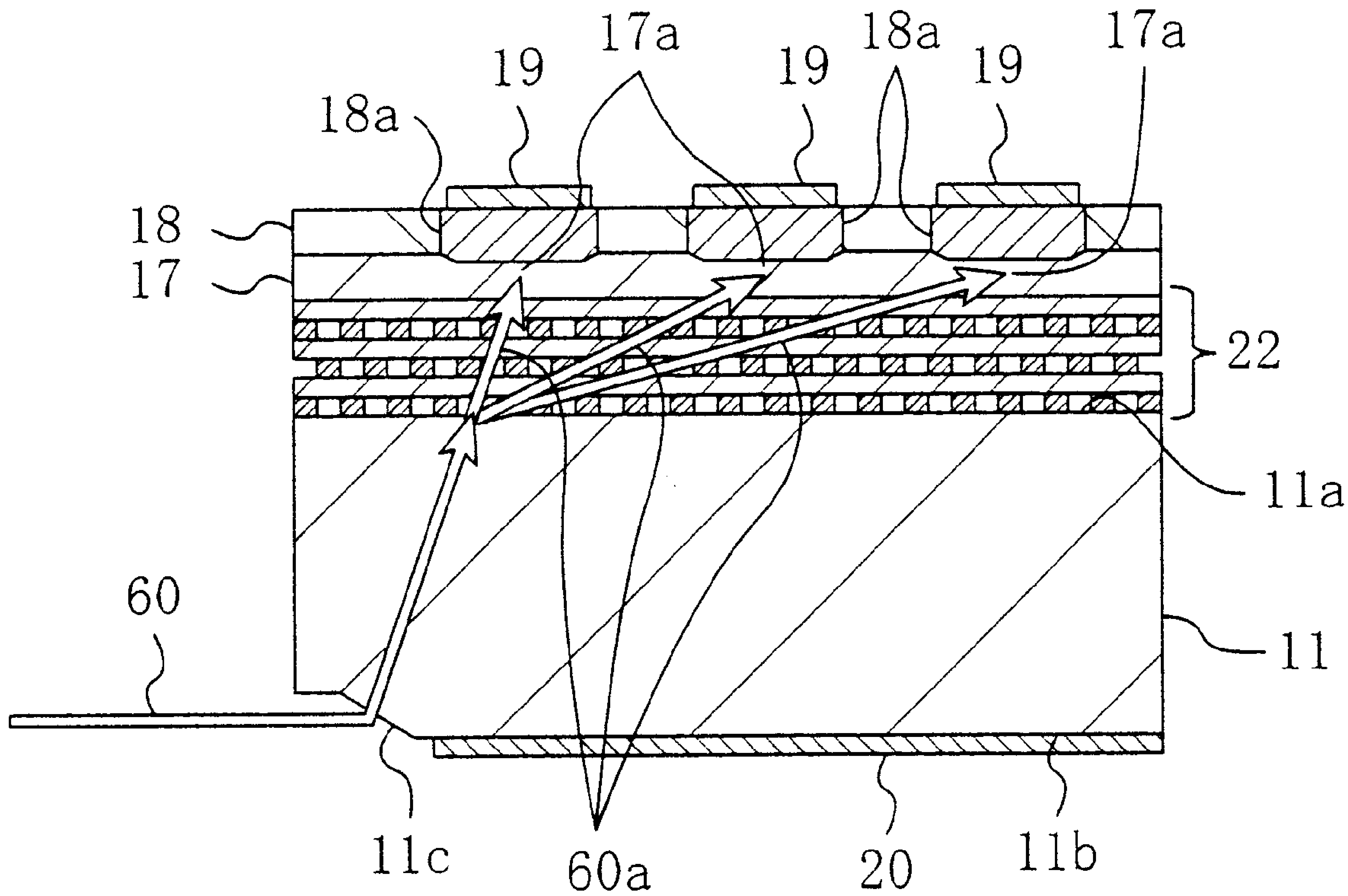


FIG. 6A

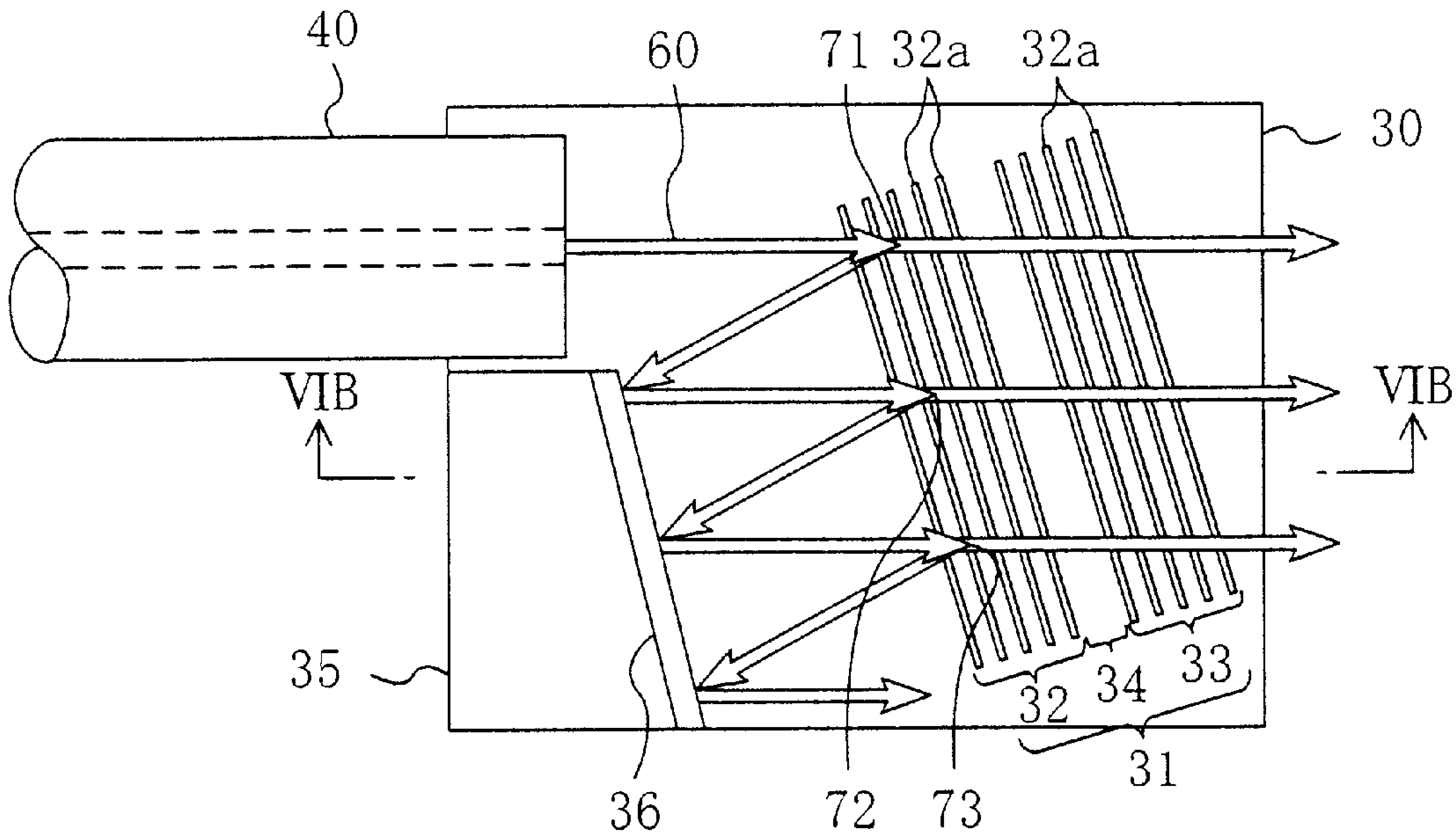
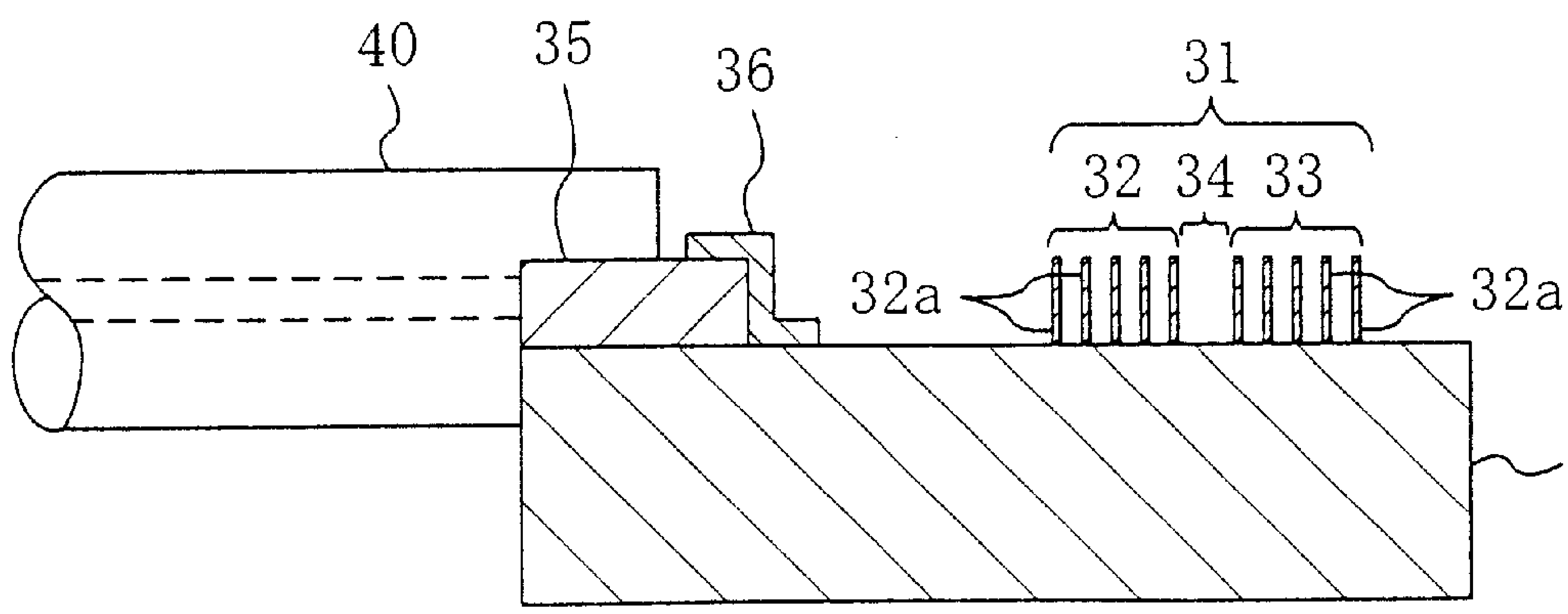

40
60
71
32a
32a
30
VIB
VIB
35
36
72
73
32
34
33
31

FIG. 6B


40
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34
33
32a
32a
30

FIG. 7A

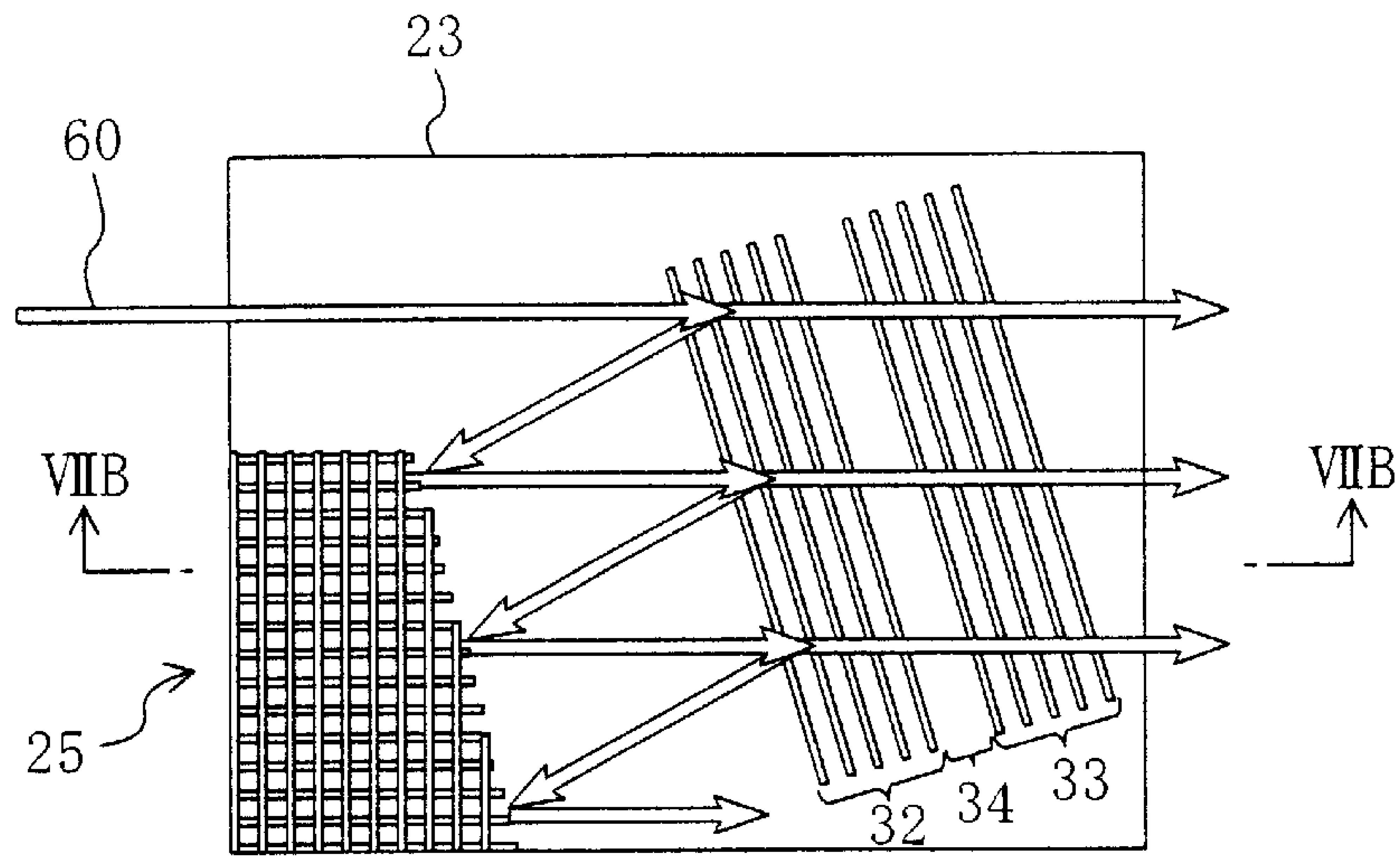


FIG. 7B

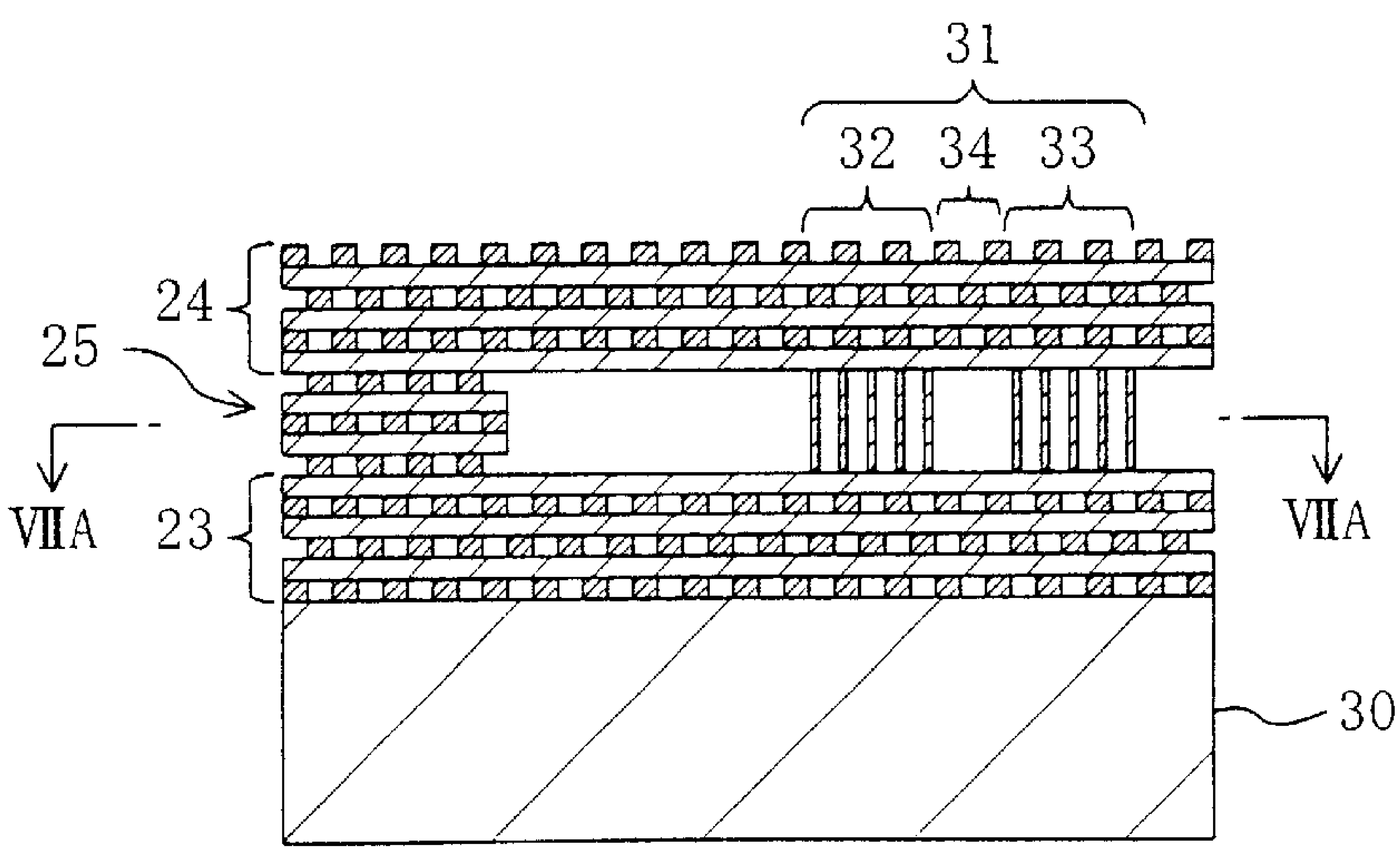
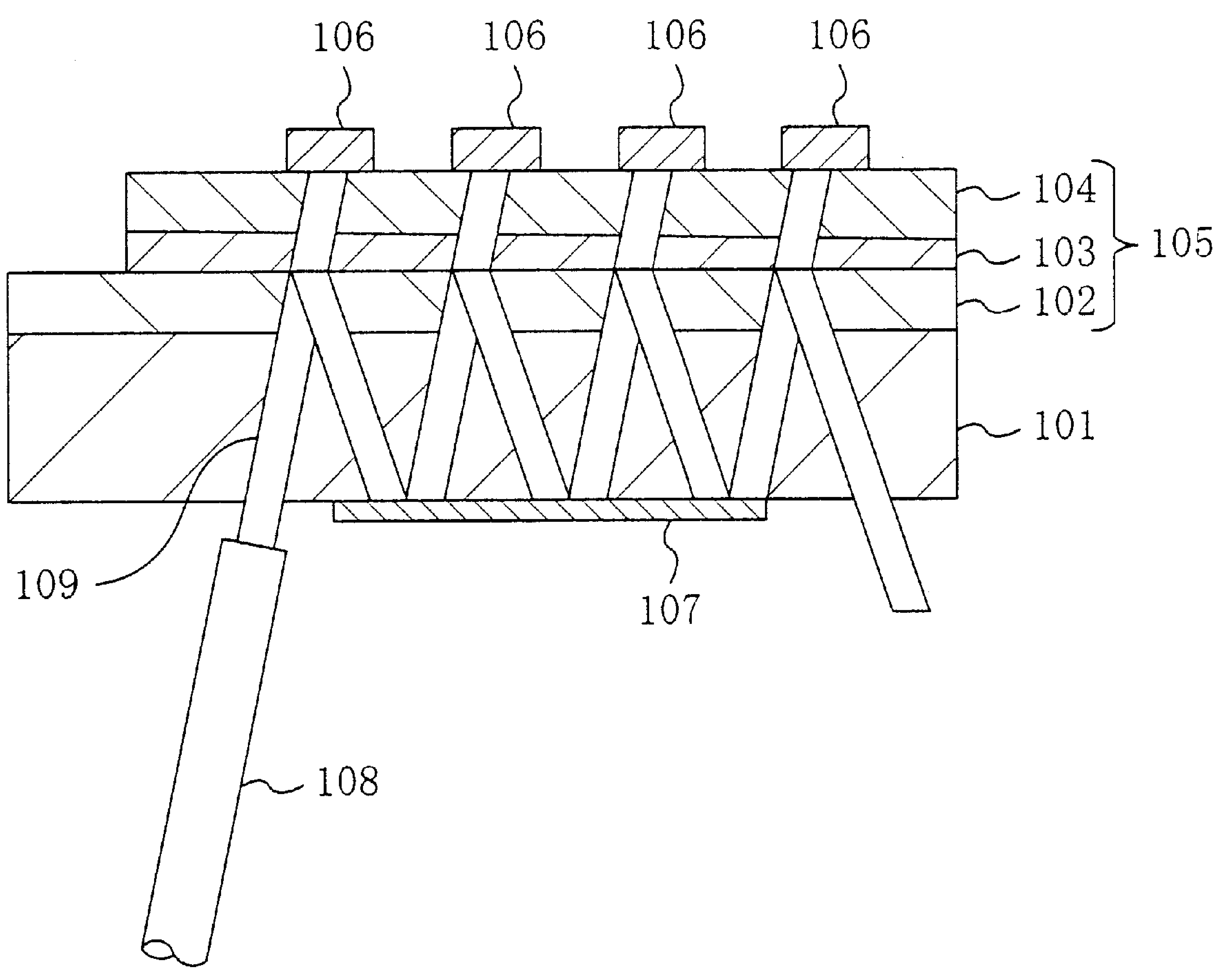


FIG. 8

PRIOR ART



DEMULTIPLEXER AND DEMULTIPLEXER-RECEIVER

BACKGROUND OF THE INVENTION

The present invention relates to a demultiplexer for separating signal light, which has been densely wavelength-multiplexed within a relatively narrow wavelength range, into multiple optical signals corresponding to their respective wavelengths and outputting those demultiplexed signals. The present invention also relates to a demultiplexer-receiver for receiving and demultiplexing wavelength-multiplexed signal light and then converting the resultant optical signals into electrical signals.

In the field of fiber-optics communications, a technique of increasing the information-carrying capacity by utilizing wavelength division multiplexing (WDM), by which a plurality of optical signals corresponding to mutually different wavelengths are combined into a single signal, is well known. Especially in recent years, a system for multiplexing four waves with respective wavelengths around 1.55 μm (each pair of which are different from each other by 3.2 nm) or even eight waves (each pair of which are different from each other by 1.6 nm) is on the verge of being implemented. And yet research and development is vigorously carried on to realize a super-high-density fiber-optics WDM network in the near future by reducing the wavelength difference to as small as 0.8 nm. Generally speaking, though, in a WDM telecommunications network, an optical signal, which has once been multiplexed on the transmitting end, should be demultiplexed on the receiving end. Accordingly, to realize a super-high-density WDM network like this, demultiplexing must be performed at a very high resolution. It is not impossible to realize that high-resolution demultiplexing using a spectroscope including a diffraction grating. However, a more cost-effective alternative would be constructing a system including either small-sized demultiplexers or an optical receiver module with those demultiplexers integrated on a semiconductor substrate, for example.

A known optical receiver module of this type, i.e., a module with demultiplexers integrated on a semiconductor substrate, is disclosed in Japanese Laid-Open Publication No. 8-46593, for example. Hereinafter, the optical receiver module will be described with reference to FIG. **8**.

FIG. **8** illustrates a cross-sectional structure for a demultiplexing and light-receiving portion of an optical receiver module as disclosed in the Japanese Laid-Open Publication No. 8-46593 identified above. As shown in FIG. **8**, a vertical cavity filter **105** is formed as a stack of lower and upper reflectors **102** and **104** and spacer layer **103** on the principal surface of a semiconductor substrate **101**. Each of the lower and upper reflectors **102** and **104** and spacer layer **103** is formed out of a semiconductor layer. On the filter **105**, multiple receivers **106** are formed just like the same number of islands. And a reflective film **107** is formed on the backside of the substrate **101** opposite to the principal surface thereof.

The filter **105** shows a transmittance of 100% against an incoming light beam with the same wavelength as one of the resonant wavelengths of the filter **105**. In this structure, each of the resonant wavelengths is determined by the uneven thickness of the spacer layer **103**. In addition, high-reflectance wavelength bands, termed "stop bands", exist around each resonant wavelength. An incoming wavelength-multiplexed light beam **109**, which has traveled through an optical fiber bundle **108**, impinges onto the backside of the substrate **101**. And only a part of the light beam **109**, of which the wavelength is equal to one of the resonant wavelengths, can be transmitted through the filter **105** and incident onto associated one of the receivers **106**. The remaining part of the light beam **109**, which has been reflected off from the filter **105**, is reflected by the reflective film **107** and then incident onto the filter **105** again. The thickness of the spacer layer **103** is not constant but changes horizontally, i.e., relative to the principal surface of the substrate **101**. Thus, the filter **105** has multiple resonant wavelengths for the respective receivers **106**. As a result, optical signals corresponding to mutually different wavelengths are received one after another.

A resonant wavelength of the vertical cavity filter **105** is given by

$$2nL\cdot\cos\theta/m$$

where n is a refractive index of the spacer layer **103**, L is the thickness of the spacer layer **103** at a given point of incidence, θ is an angle of incidence of the incoming light beam **109** (i.e., an angle formed by the light beam **109** with a normal of incidence perpendicular to the principal surface of the substrate **101**) and m is a natural number. Accordingly, if the angle θ of incidence of around 20 degrees changes by 1 degree, then the resonant wavelength of the filter **105** will change by about 0.63%. For example, when the resonant wavelength is around 1.55 μm, the change in wavelength will be about 10 nm. Stated otherwise, if the absolute value of the resonant wavelength should have a precision of 1 nm or less, then the shift in the angle θ of incidence should be 0.1 degrees or less.

The known optical receiver module, however, has the following drawbacks.

Firstly, the above-identified publication does not particularly point out a method of securing the optical fiber bundle **108** onto the semiconductor substrate **101** at a predetermined angle. Thus, it is difficult even for a skilled artisan to precisely define the angle θ of incidence of the incoming light beam **109**.

Secondly, according to the technique disclosed in the above-identified publication, the thickness of the spacer layer **103** is not controllable accurately enough. In general, a crystal-growing method for making the thickness variable relative to the surface of a substrate is already well known in the art (see U.S. Pat. No. 5,029,176, for example). However, this method is not precise enough to determine the absolute value of the resonant wavelength just as desired. In addition, it is usually hard to apply normal semiconductor device processing, in which a great number of devices are formed at a time on a single semiconductor wafer and then divided into respective chips after a wafer process, to the fabrication of the optical receiver modules. This is because a crystal-growing method allowing for a periodic thickness change of the wafer is needed in that case. But crystals can be grown in that manner just by a few methods among the numerous ones cited in the U.S. Patent identified above.

SUMMARY OF THE INVENTION

A first object of the present invention is allowing an incoming light beam to be incident onto the cavity filter of a demultiplexer or demultiplexer-receiver at a much more accurate angle.

A second object of the present invention is controlling the horizontal thickness change of at least one layer in the cavity filter precisely enough and thereby providing multiple selectable wavelengths for the filter through normal semiconductor device processing.

To achieve the first object, a first inventive demultiplexer includes: a semiconductor substrate; and a vertical cavity filter, which is formed on the principal surface of the substrate and transmits an incoming light beam with a predetermined wavelength. A resonant wavelength of the filter changes depending on at which point on the principal surface the light beam is incident. And the substrate has a recess with a slope that reflects or refracts the light beam and thereby makes the light beam incident onto the filter.

In the first demultiplexer, a slope that will make an incoming light beam incident onto a cavity filter is formed in a semiconductor substrate. The slope can be formed easily in the backside of the substrate, opposite to its principal surface, by a wet etching process, for example, so that an exactly predetermined angle is formed between the slope and the principal surface. In such a structure, if incoming signal light is incident onto the slope of the substrate, the light will be input to the vertical cavity filter while forming the predetermined angle with the principal surface and backside of the substrate with good reproducibility. As a result, a desired resonant wavelength is selectable very accurately.

In one embodiment of the present invention, the filter preferably includes: a first distributed Bragg reflector, which is formed out of a first semiconductor layer on the principal surface of the substrate; a spacer layer, which is formed out of a second semiconductor layer on the first reflector; and a second distributed Bragg reflector, which is formed out of a third semiconductor layer on the spacer layer. At least one of the first, second and third semiconductor layers preferably has its thickness changed relative to the principal surface of the substrate. In such an embodiment, a plurality of optical signals can be extracted from a multiplexed incoming light beam just as intended.

In another embodiment of the present invention, the slope is preferably a crystallographic plane that has been exposed by a wet etching process and has a predefined crystallographic plane orientation. In general, it is easy to expose a crystallographic plane of semiconductor crystals with a predefined plane orientation by wet etching. Accordingly, the slope of the substrate can also be easily defined to form a desired angle with the backside of the substrate, for example.

To achieve the second object, a second inventive demultiplexer includes: a semiconductor substrate; and a photonic crystalline layer, which is formed on the principal surface of the substrate and transmits an incoming light beam with a predetermined wavelength. A wavelength at an edge of a photonic band of the photonic crystalline layer changes in a direction parallel to the principal surface of the substrate.

The second demultiplexer includes a photonic crystalline layer instead of the vertical cavity filter of the first demultiplexer. As is well known in the art, photonic crystals form a band structure responsive to the energy of photons. Accordingly, photons, included in a special band gap called "photonic band gap", cannot exist in the crystals. That is to say, radiation with a wavelength corresponding to the energy contained in the photonic band gap is totally reflected by the photonic crystals. On the other hand, radiation with a wavelength corresponding to the energy not contained in the photonic band gap (i.e., the energy contained in the photonic bands) is transmitted through the photonic crystals. Accordingly, in the photonic crystalline layer, if the band edge of the photonic band gap changes parallelly to the surface of the substrate, then the range where the light beam is transmitted also changes. In this manner, multiple optical signals corresponding to desired wavelengths can be extracted sequentially.

In one embodiment of the present invention, the substrate preferably has a recess with a slope that reflects or refracts the light beam and thereby makes the light beam incident onto the photonic crystalline layer. In such an embodiment, a plurality of optical signals can be extracted just as intended from even a relatively densely wavelength-multiplexed incoming light beam.

In this particular embodiment, the photonic crystalline layer is preferably made up of a plurality of dielectric or semiconductor fine lines that are arranged like a lattice. And the width of each said fine line or a gap between adjacent ones of the fine lines preferably changes in a direction parallel to the principal surface of the substrate. In such an embodiment, the band edge of the photonic band gap of the photonic crystalline layer can be changed in the direction parallel to the principal surface. Unlike the vertical cavity filter, the thickness of the photonic crystalline layer is constant horizontally. Accordingly, the photonic crystalline layer can be formed by horizontal patterning and is far more compatible with normal semiconductor device processing in which a great number of devices with the same structure are formed at a time on a single wafer.

In another embodiment of the present invention, the slope is preferably a crystallographic plane that has been exposed by a wet etching process and has a predefined crystallographic plane orientation. In general, it is easy to expose a crystallographic plane of semiconductor crystals with a predefined plane orientation by wet etching. Accordingly, the slope of the substrate can also be easily defined to form a desired angle with the backside of the substrate, for example.

To achieve the first and second objects, a third inventive demultiplexer includes a horizontal cavity filter, which is formed on a substrate and transmits a part of an incoming light beam traveling in a direction substantially parallel to the surface. The part transmitted has a predetermined wavelength. The filter includes: a first distributed Bragg reflector, which is formed to make an optical path of the light beam parallel to the surface of the substrate; and a second distributed Bragg reflector, which is formed to be spaced apart from the first reflector.

The third inventive demultiplexer includes a horizontal cavity filter for selectively transmitting a light beam traveling in a direction substantially parallel to the surface of the substrate. Accordingly, when a light beam is externally entering the demultiplexer through an optical fiber bundle, the angle of incidence can be set to a desired one easily and just as intended. As a result, a ray with a desired wavelength can be easily selected from a densely wavelength-multiplexed incoming light beam. In addition, the horizontal cavity filter can be formed by horizontal patterning and is much more compatible with normal semiconductor device processing in which a great number of devices with the same structure are formed at a time on a single wafer.

In one embodiment of the present invention, each of the first and second distributed Bragg reflectors is preferably formed by arranging a plurality of dielectric or semiconductor thin plate members on the substrate at regular intervals so that the plate members cross the optical path. In this manner, the horizontal cavity filter is easily implementable.

In another embodiment of the present invention, a resonant wavelength of the filter preferably changes depending on at which point on the substrate the light beam is incident. In such an embodiment, a plurality of optical signals can be extracted from a multiplexed incoming light beam just as intended.

In this particular embodiment, the space between the first and second distributed Bragg reflectors preferably changes and is preferably tapered or stepped in the direction parallel to the surface of the substrate.

In still another embodiment, the third demultiplexer preferably further includes: a first photonic crystalline layer, which is formed between the substrate and the filter; and a second photonic crystalline layer, which is formed on the filter. In this case, if the photonic band gaps of the first and second photonic crystalline layers, sandwiching the horizontal cavity filter vertically, have such energies as covering the entire wavelength range of the incoming light beam, then the light beam entering the filter can be confined within the filter. As a result, the loss of the incoming light beam can be reduced.

To achieve the first object, a first inventive demultiplexer-receiver includes: a semiconductor substrate; a vertical cavity filter, which is formed on the principal surface of the substrate and transmits an incoming light beam with a predetermined wavelength; and a plurality of light-receiving areas defined on the filter. A resonant wavelength of the filter changes depending on at which point on the principal surface the light beam is incident. And the substrate has a recess with a slope that reflects or refracts the light beam and thereby makes the light beam incident onto the filter.

In the first demultiplexer-receiver, a slope is also formed in the backside of a semiconductor substrate as in the first inventive demultiplexer. In this structure, if a light beam is incident onto the slope of the substrate, the light beam will be input to a vertical cavity filter while forming a predetermined angle with the principal surface and backside of the substrate with good reproducibility. As a result, a desired resonant wavelength can be selected.

In one embodiment of the present invention, the first demultiplexer-receiver preferably further includes a light-absorbing layer and a window layer that are formed in this order on the filter. The window layer preferably includes a plurality of doped regions that are defined like islands. And the light-receiving areas are preferably respective parts of the light-absorbing layer that are located under the doped regions. In this manner, the respective optical signals, resulting from the demultiplexing by the vertical cavity filter, can be received just as intended. In addition, the areas at which the demultiplexed optical signals are received are integrated with the demultiplexer monolithically, and the demultiplexed optical signals (i.e., light beams) impinge through the slope onto the light-receiving areas. Accordingly, the window layer does not function as a window for transmitting the signal light therethrough but as a passivation film that can reduce leakage current.

To achieve the second object, a second inventive demultiplexer-receiver includes: a semiconductor substrate; a photonic crystalline layer, which is formed on the principal surface of the substrate and transmits an incoming light beam with a predetermined wavelength; and a plurality of light-receiving areas defined on the photonic crystalline layer. The substrate has a recess with a slope that reflects or refracts the light beam and thereby makes the light beam incident onto the photonic crystalline layer.

In the second demultiplexer-receiver, the second inventive demultiplexer is integrated monolithically with the light-receiving areas for receiving the optical signals resulting from the demultiplexing by the second demultiplexer.

Thus, the second demultiplexer-receiver can attain the same effects as those of the second demultiplexer.

In one embodiment of the present invention, the second demultiplexer-receiver preferably further includes a light-absorbing layer and a window layer that are formed in this order on the photonic crystalline layer. The window layer preferably includes a plurality of doped regions that are defined like islands. And the light-receiving areas are preferably respective parts of the light-absorbing layer that are located under the doped regions.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a cross-sectional view illustrating a structure for a demultiplexer according to a first embodiment of the present invention.

FIG. **2** is a cross-sectional view illustrating a structure for a demultiplexer-receiver according to a second embodiment of the present invention.

FIG. **3** is a cross-sectional view illustrating a structure for a demultiplexer according to a third embodiment of the present invention.

FIGS. **4**A through **4**C are graphs schematically illustrating how a photonic crystalline layer extracts optical signals from wavelength-multiplexed signal light for respective points of incidence in the demultiplexer of the third embodiment.

FIG. **5** is a cross-sectional view illustrating a structure for a demultiplexer-receiver according to a fourth embodiment of the present invention.

FIGS. **6**A and **6**B are respectively a plan view and a ross-sectional view, taken along the line VIB—VIB in FIG. **6**A, of a demultiplexer according to a fifth embodiment of the present invention.

FIGS. **7**A and **7**B are cross-sectional views, taken along the lines VIIA—VIIA and VIIB—VIIB in FIGS. **7**B and **7**A, respectively, of a demultiplexer according to a sixth embodiment of the present invention.

FIG. **8** is a cross-sectional view illustrating a structure for a known demultiplexer-receiver.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Embodiment 1

Hereinafter, a first embodiment of the present invention will be described with reference to FIG. **1**.

FIG. **1** illustrates a cross-sectional structure for a demultiplexer according to the first embodiment. As shown in FIG. **1**, a vertical cavity filter **15** is formed by stacking first distributed Bragg reflector **12**, spacer layer **13**. and second distributed Bragg reflector **14** in this order on a first principal surface **11***a* of a semiconductor substrate **11** of GaAs, for example. Each of the first and second reflectors **12** and **14** may be formed by alternately and repeatedly stacking semiconductor layers of GaAs and AlAs, respectively. A total thickness of these semiconductor layers (the number of which may be about 30 to about 40) may be from about 3.89 μm to about 5.1 μm. The spacer layer **13** may be formed out of a semiconductor layer of GaAs with a thickness of about 467 nm.

In a second principal surface **11***b* of the substrate **11**, which is on the opposite side to the first principal surface **11***a*, a recess with a slope **11***c* that reflects an incoming light beam **60** is formed. And a metal reflective film **16** is deposited over the entire second principal surface **11***b* as well as inside the recess.

The incoming light beam **60**, which has traveled through an optical fiber bundle (not shown), for example, enters the demultiplexer in a direction parallel to the second principal surface **11***b* of the substrate **11**. Then, the beam **60** is partially reflected by a region of the metal reflective film **16** on the slope **11***c*. As a result, that reflected part of the incoming light beam **60** is incident onto the vertical cavity filter **15**. On the other hand, the remaining part of the incoming light beam **60**, which has not been incident onto the filter **15**, will be reflected off from the metal reflective film **16** again and then incident onto the filter **15**.

According to the first embodiment, multiple optical signals corresponding to mutually different wavelengths have been multiplexed in the incoming light beam **60**. In the following illustrative example, three optical signals associated with first, second and third wavelengths **λ1**, **λ2** and **λ3**, respectively (where λ1>λ2>λ3) are supposed to have been multiplexed in the incoming light beam **60** for the sake of simplicity. Each of the GaAs and AlAs layers in the first and second reflectors **12** and **14** has its thickness determined so that an optical length thereof defined with the tilt of the optical path of the incoming light beam **60** taken into account (i.e., a product of the distance over which the light beam travels through the layer and refractive index thereof) is one-fourth as long as the second wavelength **λ2** (i.e., the center wavelength for the optical signals).

In this embodiment, the difference between first and second wavelengths **λ1** and **λ2** and between second and third wavelengths **λ2** and **λ3** may be as small as 1 nm, for example.

Accordingly, the stop bands (i.e., high-reflectance wavelength regions) of the first and second reflectors **12** and **14** can fall within the range between the first and third wavelengths **λ1** and **λ3**.

As shown in FIG. **1**, the thickness of the spacer layer **13** changes horizontally, i.e., relative to the first principal surface **11***a*. As a result, the optical lengths will be respectively **λ1**, **λ2** and **λ3** at first, second and third points **71**, **72** and **73** of incidence on the filter **15** on which the incoming light beam **60** is incident. Thus, at the first point **71** of incidence on the filter **15**, the resonant wavelength will be **λ1**. Accordingly, only the optical signal associated with the first wavelength **λ1** is transmitted through the filter **15**, while the optical signals associated with the second and third wavelengths **λ2** and **λ3** are not input to the filter **15** but reflected off. In the same way, if the beam **60** is incident at the second point **72**, then only the optical signal associated with the second wavelength **λ2** is transmitted through the filter **15**. And if the beam **60** is incident at the third point **73**, then only the optical signal associated with the third wavelength **λ3** is transmitted through the filter **15**.

The primary feature of this embodiment is the slope **11***c* that has been formed in the second principal surface **11***b* of the substrate **11**, because the slope **11***c* determines an angle at which the incoming light beam **60** is incident onto the filter **15**. For example, suppose the substrate **11** has a (001) crystallographic plane as the second principal surface **11***b* and a (112) crystallographic plane as the slope **11***c* of the second principal surface **11***b*, respectively. The slope **11***c* may be exposed as a result of a wet etching process using an etchant containing hydrogen chloride (HCl) and nitric acid (HNO_3) at a volume ratio of 4:1. In that case, the slope **11***c* will form exactly an angle of 35.3 degrees with the second principal surface **11***b*. Accordingly, if the incoming light beam **60**, traveling parallelly to the second principal surface **11***b*, is reflected by the slope **11***c* of the metal reflective film **16**, then the reflected beam **60** will be incident onto the filter **15** with an angle of 19.4 degrees formed with a normal of incidence perpendicular to the first and second principal surfaces **11***a* and **11***b*.

In this case, if the externally incoming light beam **60** is input through an optical fiber bundle, for example, then it is easy to hold the fiber bundle on a plane parallel to the substrate **11**. In this manner, the angle at which the incoming light beam **60** is incident onto the filter **15** can be kept constant very easily and highly accurately. Thus, the vertical cavity filter **15** can have much more accurate resonant wavelengths. Consequently, the present invention is effectively applicable to super-high-density WDM network in which the difference in wavelength between multiplexed optical signals should be as small as about 0.8 nm.

In the first embodiment, the slope **11***c* is formed in the second principal surface **11***b*. Alternatively, the recess with the slope **11***c* may be formed in a side face of the semiconductor substrate **11**.

Embodiment 2

Hereinafter, a second embodiment of the present invention will be described with reference to FIG. **2**.

FIG. **2** illustrates a cross-sectional structure for a demultiplexer-receiver according to the second embodiment. In FIG. **2**, the same member as the counterpart illustrated in FIG. **1** is identified by the same reference numeral and the description thereof will be omitted herein. As shown in FIG. **2**, the demultiplexer-receiver of the second embodiment has a monolithic structure in which a semiconductor layer, including light-receiving areas, is formed on the vertical cavity filter **15** of the demultiplexer of the first embodiment. More specifically, a light-absorbing layer **17** of n-type lightly doped InGaAs with a thickness of about 2.5 μm, for example, and a window layer **18** of n-type lightly-doped InP with a thickness of about 1.5 μm, for example, are deposited in this order on the second distributed Bragg reflector **14** of the filter **15**. In the window layer **18**, three p-type doped regions **18***a* are defined just like so many islands by doping and diffusing a p-type dopant such as Zn. Each of the p-type doped regions **18***a* may have a diameter of about 80 μm. And respective areas of the light-absorbing layer **17**, which are located under the p-type doped regions **18***a*, serve as the light-receiving areas **17***a*. Furthermore, negative electrodes **19** are formed out of an evaporated and deposited metal film on the respective p-type doped regions **18***a*.

At an edge of a second principal surface **11***b* of a semiconductor substrate **11** on the opposite side of a first principal surface **11***a* thereof, a notch with a slope **11***c* that refracts an incoming light beam **60** is formed. At another edge of the second principal surface **11***b* on the opposite side of the notch, a positive electrode **20** is formed out of another evaporated and deposited metal film.

The incoming light beam **60**, which has traveled through an optical fiber bundle (not shown), for example, enters the demultiplexer-receiver in a direction. parallel to the second principal surface **11***b* of the substrate **11**. Then, the beam **60** is refracted at the slope **11***c*. As a result, part of the incoming light beam **60** is incident onto the vertical cavity filter **15**. The remaining part of the incoming light beam **60**, which has not been incident onto the filter **15**, will also be incident onto the filter **15** afterwards. In this manner, if conditions for total reflection are met, a reflectance of 100% can be obtained without providing any reflective film on the second principal surface **11***b*.

Suppose three optical signals corresponding to first, second and third wavelengths **λ1**, **λ2** and **λ3**, respectively, have been multiplexed in the incoming light beam **60** as in the first embodiment. If the beam **60** is incident at the first point

71, only the optical signal associated with the first wavelength λ**1** is transmitted through the vertical cavity filter **15** as described above. In the same way, if the beam **60** is incident at the second point **72**, then only the optical signal associated with the second wavelength λ**2** is transmitted through the filter **15**. And if the beam **60** is incident at the third point **73**, then only the optical signal associated with the third wavelength λ**3** is transmitted through the filter **15**.

After having been transmitted through the filter **15**, these optical signals corresponding to respectively predetermined wavelengths are received at their associated light-receiving areas **17***a* and then detected as photocurrents flowing between the positive and negative electrodes **20** and **19**.

The primary feature of this embodiment is the slope **11***c* that has been formed at the edge of the second principal surface **11***b* of the substrate **11**, because the slope **11***c* determines an angle at which the incoming light beam **60** is incident onto the filter **15**. For example, suppose the slope **11***c* is a (112) crystallographic plane that has been exposed by a wet etching process. In that case, the slope **11***c* will form exactly an angle of 35.3 degrees with the second principal surface **11***b*. Accordingly, if the incoming light beam **60**, traveling parallelly to the second principal surface **11***b*, is refracted at the slope **11***c*, then the refracted beam **60** will be incident onto the filter **15** with an angle of 49.0 degrees formed with a normal of incidence perpendicular to the first and second principal surfaces **11***a* and **11***b*.

In this case, if the externally incoming light beam **60** is input through an optical fiber bundle, for example, then it is easy to hold the fiber bundle on a plane parallel to the substrate **11**. In this manner, the angle at which the incoming light beam **60** is incident onto the filter **15** can be kept constant very easily and highly accurately. Thus, the vertical cavity filter **15** can have much more accurate resonant wavelengths. Consequently, the present invention is effectively applicable to even a super-high-density WDM network in which the wavelength difference between multiplexed optical signals should be as small as about 0.8 nm.

In the second embodiment, the slope **11***c* is formed as a part of the notch. Alternatively, the slope **11***c* may be formed in a recess as in the first embodiment. In that case, a metal reflective film **16** may be formed on the slope **11***c*.

Also, in the second embodiment, the slope **11***c* is formed at an edge of the second principal surface **11***b*. Alternatively, a recess with the slope **11***c* may be formed in a side face of the substrate **11**.

Embodiment 3

Hereinafter, a third embodiment of the present invention will be described with reference to FIG. **3** and FIGS. **4**A through **4**C.

FIG. **3** illustrates a cross-sectional structure for a demultiplexer according to the third embodiment. In FIG. **3**, the same member as the counterpart illustrated in FIG. **1** is identified by the same reference numeral and the description thereof will be omitted herein. As shown in FIG. **3**, the demultiplexer of the third embodiment includes a photonic crystalline layer **21**, not the vertical cavity filter **15**, on a first principal surface **11***a* of a semiconductor substrate **11**. The photonic crystalline layer **21** is also provided to selectively extract a plurality of optical signals corresponding to multiple wavelengths from the input wavelength-multiplexed signal light.

The photonic crystalline layer **21** is formed as a stack of a number of (e.g., eight) lattice layers. In each of the lattice layers, multiple dielectric (e.g., silicon dioxide (SiO_2)) fine lines with a width of about 360 nm or multiple semiconductor (e.g., GaAs) fine lines with a width of about 170 nm are arranged to form a lattice. As used herein, the "photonic crystalline layer" is a multilayer structure in which the locations of the fine lines in the n^{th} layer (or the $(n+1)^{th}$ layer) shift from those of the fine lines in the $(n+2)^{th}$ layer (or the $(n+3)^{th}$ layer) by a half period. It should be noted that n is herein an integer equal to or greater than 1. In addition, the widths of the fine lines and gaps between adjacent ones of them change in a direction parallel to the first principal surface **11***a*. Accordingly, the wavelength at an edge of the photonic band of the photonic crystalline layer **21** changes parallelly to the first principal surface **11***a*, i.e., depending on a point of the photonic crystalline layer **21** on which a light beam has been incident.

The incoming light beam **60**, which has traveled through an optical fiber bundle (not shown), for example, enters the demultiplexer in a direction parallel to the second principal surface **11***b* of the substrate **11**. Then, the beam **60** is partially reflected by a region of the metal reflective film **16** on the slope **11***c*. As a result, that reflected part of the incoming light beam **60** is incident onto the photonic crystalline layer **21**. On the other hand, the remaining part of the incoming light beam **60**, which has not been incident onto the layer **21**, will be reflected off from the metal reflective film **16** again and then incident onto the layer **21**.

Hereinafter, it will be described with reference to FIGS. **4**A through **4**C how the photonic crystalline layer **21** extracts respective optical signals from the incoming wavelength-multiplexed light beam **60**. As in the first embodiment, three optical signals associated with three different wavelengths λ**1**, λ**2** and λ**3** have been multiplexed in the incoming light beam **60**. In FIGS. **4**A through **4**C, the abscissa indicates the wavelength, while the ordinate indicates the reflectance of the photonic crystalline layer **21**.

First, as shown in FIG. **4**A, if the incoming light beam **60** is incident at the first point **71** on the photonic crystalline layer **21**, then light beams with the second and third wavelengths λ**2** and λ**3** are totally reflected by the photonic crystalline layer **21**. This is because the second and third wavelengths λ**2** and λ**3** correspond to respective energies included in a first photonic band gap defined by band edge wavelengths λA and λB. On the other hand, since a light beam with the first wavelength λ**1** corresponds to an energy smaller than the first photonic band gap (i.e., an energy included in a photonic band), the reflectance of the light beam with the first wavelength λ**1** will be almost 0%. As a result, only the light beam with the first wavelength λ**1** is transmitted through the photonic crystalline layer **21**.

Next, as shown in FIG. **4**B, if the incoming light beam **60** is incident at the second point **72** on the photonic crystalline layer **21**, then the light beam with the third wavelength λ**3** is totally reflected by the photonic crystalline layer **21**. This is because the third wavelength λ**3** corresponds to an energy included in a second photonic band gap defined by band edge wavelengths λC and λD, which are shorter than the counterparts λA and λB of the first photonic band gap. That is to say, the second photonic band gap corresponds to energies higher than those represented by the first photonic band gap. As a result, the light beams with the first and second wavelengths λ**1** and λ**2** are reflected at almost 0% this time. However, since the light beam with the first wavelength λ**1** has already been transmitted through the photonic crystalline layer **21**, only the light beam with the second wavelength λ**2** is transmitted through the photonic crystalline layer **21**.

Then, as shown in FIG. **4**C, if the incoming light beam **60** is incident at the third point **73** on the photonic crystalline layer **21**, then none of the light beams is reflected by the photonic crystalline layer **21**. This is because the first, second and third wavelengths λ**1**, λ**2** and λ**3** all correspond to energies that are not included in a third photonic band gap (i.e., energies within the photonic band) defined by band edge wavelengths λE and λF, which are even shorter than the counterparts λC and λD of the second photonic band gap. As a result, the remaining light beam that has not been transmitted yet, i.e., the light beam with the third wavelength λ**3**, is transmitted through the photonic crystalline layer **21** this time.

As described above, the photonic crystalline layer **21** is used according to the third embodiment instead of the vertical cavity filter. Thus, if the photonic crystalline layer **21** has been patterned in a direction parallel to the first principal surface **11***a* of the substrate **11**, the wavelengths λA, λB and so on at the edges of photonic bands can be changed.

That is to say, if the vertical cavity filter **15** is used as in the first embodiment, then the filter **15** should have its thickness increased or decreased to make the resonant wavelength changeable relative to the first principal surface **11***a*. In contrast, if the photonic crystalline layer **21** is used, the photonic band edges, determining the resonant wavelengths, can be changed by forming the layer **21** through a patterning process in the direction parallel to the first principal surface **11***a*. As a result, the demultiplexer of the third embodiment does not have to have its thickness changed unlike the vertical cavity filter **15**. Accordingly, this embodiment is much more compatible with normal semiconductor device processing, in which a great number of devices are formed at a time on a single semiconductor wafer.

In the third embodiment, the photonic crystalline layer **21** is formed in such a manner as to make wavelengths at respective edges of the photonic bands changeable in the direction parallel to the first principal surface **11***a*. Alternatively, the densely wavelength-multiplexed incoming light beam may be dispersed anomalously at various angles by utilizing Super Prism effects.

In the third embodiment, the slope **11***c* is formed in the second principal surface **11***b*. Alternatively, the recess with the slope **11***c* may be formed in a side face of the semiconductor substrate **11**.

Embodiment 4

Hereinafter, a fourth embodiment of the present invention will be described with reference to FIG. **5**.

FIG. **5** illustrates a cross-sectional structure for a demultiplexer-receiver according to the fourth embodiment. In FIG. **5**, the same member as the counterpart illustrated in FIG. **3** is identified by the same reference numeral. As shown in FIG. **5**, the demultiplexer-receiver of the fourth embodiment has a monolithic structure in which a semiconductor layer, including light-receiving areas, is formed on a photonic crystalline layer **22**.

The photonic crystalline layer **22** is formed as a stack of a number of lattice layers. In each of the lattice layers, multiple dielectric (e.g., SiO_2) fine lines with a width of about 360 nm or multiple semiconductor (e.g., GaAs) fine lines with a width of about 170 nm are arranged to form a lattice.

The photonic crystalline layer **22** is a multilayer structure in which the locations of the fine lines in the nth layer (or the $(n+1)^{th}$ layer) shift from those of the fine lines in the $(n+2)^{th}$ layer (or the $(n+3)^{th}$ layer) by a half period.

A light-absorbing layer **17** of n-type lightly doped InGaAs with a thickness of about 2.5 μm, for example, and a window layer **18** of n-type lightly-doped InP with a thickness of about 1.5 μm, for example, are deposited in this order on the photonic crystalline layer **22**. In the window layer **18**, three p-type doped regions **18***a* are defined just like so many islands by doping and diffusing a p-type dopant such as Zn. Each of the p-type doped regions **18***a* may have a diameter of approximately 30 μm. And respective areas of the light-absorbing layer **17**, which are located under the p-type doped regions **18***a*, serve as light-receiving areas **17***a*. Furthermore, negative electrodes **19** are formed out of an evaporated and deposited metal film on the respective p-type doped regions **18***a*.

At an edge of a second principal surface **11***b* of a semiconductor substrate **11**, a notch with a slope **11***c* that refracts an incoming light beam **60** is formed. On the second principal surface **11***b*, a positive electrode **20** is formed out of another evaporated and deposited metal film.

The incoming light beam **60**, which has traveled through an optical fiber bundle (not shown), for example, enters the demultiplexer-receiver in a direction parallel to the second principal surface **11***b* of the substrate **11**. Then, the beam **60** is refracted at the slope **11***c* and incident onto the photonic crystalline layer **22**.

The photonic crystalline layer **22** of the fourth embodiment realizes demultiplexing by taking advantage of anomalous dispersion effects. The photonic crystals exhibit the anomalous dispersion effects, by which a refractive index greatly changes within an extremely narrow wavelength range. Thus, thanks to the anomalous dispersion effects, the densely wavelength-multiplexed incoming light beam **60** can be dispersed at a broad variety of angles. Accordingly, if the dispersed rays **60***a* of the incoming light beam **60** outgo through the photonic crystalline layer **22** to be incident onto the respective light-receiving areas **17***a*, then those rays with mutually different wavelengths can be detected as photocurrents flowing between the negative and positive electrodes **19** and **20**.

In this embodiment, the photonic crystalline layer **22** is formed as a stack of lattice layers so that dielectric or semiconductor fine lines are arranged like a lattice in each of these layers. In this case, it is not easy to form the light-absorbing and window layers **17** and **18** on the photonic crystalline layer **22** by a crystal-growing process. However, such a structure is easily obtained by utilizing a wafer bonding technique.

In the fourth embodiment, the slope **11***c* is formed at the edge of the second principal surface **11***b*. Alternatively, a recess with the slope **11***c* may be formed in a side face of the substrate **11**.

Embodiment 5

Hereinafter, a fifth embodiment of the present invention will be described with reference to FIGS. **6**A and **6**B.

FIGS. **6**A and **6**B respectively illustrate a planar layout and a cross-sectional structure, taken along the line VIB—VIB in FIG. **6**A, of a demultiplexer according to the fifth embodiment. As shown in FIGS. **6**A and **6**B, an optical fiber bundle **40**, through which an incoming light beam **60** travels in a direction parallel to the surface of a substrate **30** of Si or GaAs, for example, is secured to an upper edge of the substrate **30**. And a horizontal cavity filter **31** is formed on the substrate **30** to receive the incoming light beam **60** at a predetermined angle at an edge thereof.

The horizontal cavity filter **31** includes first and second distributed Bragg reflectors **32** and **33**. Each of the first and second distributed Bragg reflectors **32** and **33** is made up of a plurality of thin plate members **32***a* that are placed to cross the optical path of the light beam **60** with each adjacent pair of members **32***a* spaced by about 447 nm. The space **34** between the first and second reflectors **32** and **33** is not constant but varied. In the illustrated embodiment, each thin plate member **32***a* is made of a dielectric material (e.g., SiO_2) with a thickness of about 307 nm or a semiconductor material (e.g., GaAs) with a thickness of about 127 nm.

Furthermore, a reflective block member **35** is placed at such a position on the substrate **30** that the light, reflected from the first reflector **32**, will be incident onto the first reflector **32** again. A metal reflective film **36** has been deposited on a surface of the block member **35** that faces the horizontal cavity filter **31**. In this case, the block member **35** may be made of the same material as the thin plate members **32***a*.

The incoming light beam **60**, which has traveled through the optical fiber bundle **40** and in which a plurality of optical signals associated with mutually different wavelengths have been multiplexed, is partially incident onto the horizontal cavity filter **31**. The other part of the light beam **60** is reflected by the metal reflective film **36** on the reflective block member **35** and then incident onto the filter **31**.

As in the first embodiment, optical signals associated with the first, second and third wavelengths λ**1**, λ**2** and λ**3** (where λ1>λ2>λ3) are supposed to have been multiplexed in the incoming light beam **60**. The thickness of each of the thin plate members **32***a* for the first and second distributed Bragg reflectors **32** and **33** and the space between adjacent ones of the members **32***a* are both defined so that the optical lengths thereof will be one-fourth as long as the wavelength. Specifically, the optical length as defined with the tilt of the optical path of the incoming light beam **60** taken into account (i.e., a product of the distance over which the light beam **60** travels through the member **32***a* and the refractive index thereof) or the space between the members **32***a* themselves shall be one-fourth as long as the second wavelength λ**2** (i.e., the center wavelength of the signals). In this case, supposing the gap between adjacent ones of the thin plate members **32***a* has been filled with the air, the optical length will be equal to the actual space between them.

According to the fifth embodiment, the difference between first and second wavelengths λ**1** and λ**2** or between the second and third wavelengths λ**2** and λ**3** may be as small as 1 nm. Thus, the stop bands (i.e., high-reflectance wavelength ranges) of the first and second distributed Bragg reflectors **32** and **33** can afford to cover all of the first, second and third wavelengths λ**1**, λ**2** and λ**3**.

In addition, as shown in FIG. **6**A, the space **34** has its width changed within a plane parallel to the substrate **30**. Accordingly, when the incoming light beam **60** is incident onto the filter **31** at a first point **71**, the resultant optical length will be λ**1**. When the beam **60** is incident at a second point **72**, the optical length will be λ**2**. And when the beam **60** is incident at a third point **73**, the optical length will be λ**3**. That is to say, since the resonant wavelength is λ**1** when the beam **60** is incident onto the filter **31** at the first point **71**, only the light beam with the first wavelength λ**1** is transmitted through the filter **31**. On the other hand, the light beams with the second and third wavelengths λ**2** and λ**3** are not input to the filter **31** but reflected off. In the same way, when the beam **60** is incident onto the filter **31** at the second point **72**, only the light beam with the second wavelength λ**2** is transmitted through the filter **31**. And when the beam **60** is incident onto the filter **31** at the third point **72**, only the light beam with the third wavelength λ**3** is transmitted through the filter **31**.

In this case, the space **34** between the reflectors **32** and **33** in the filter **31** is preferably changed in such a manner as to have its width gradually increased (i.e., tapered) from one end of the space **34** toward the other.

More preferably, the space **34** between the first and second reflectors **32** and **33** is divided lengthwise into at least the same number of sectors as that of the signals to be extracted. And each adjacent pair of sectors should have mutually different widths so that the space **34** between the reflectors **32** and **33** changes stepwise. It should be noted that the width should not change within the same sector. In such a case, since each of the sectors, corresponding to the respective points of incidence **71**, **72** and **73** of the light beams to be transmitted, has a constant width, the wavelength does not change, either, within the sector. Accordingly, a good margin is ensured for misalignment of the reflectors **32** and **33** during a fabrication process, thus increasing the production yield.

The demultiplexer of the first embodiment includes the vertical cavity filter **15**, in which the distributed Bragg reflectors are stacked one upon the other vertically to the surface of the substrate. On the other hand, the demultiplexer of the fifth embodiment includes the horizontal cavity filter **31**, in which the distributed Bragg reflectors are arranged side by side in a direction parallel to the surface of the substrate.

When the horizontal cavity filter **31** is used, the angle of incidence of the incoming light beam **60** may be determined within a plane parallel to the surface of the substrate. Accordingly, if a V-groove is formed as a guide in the upper part of the substrate **30** to mount the optical fiber bundle **40** therein, then the angle of incidence can be defined precisely.

In addition, only by designing an appropriate mask pattern, the space **34** between the first and second distributed Bragg reflectors **32** and **33** can be changed so that the resonant wavelength will change within a plane parallel to the substrate. Unlike the vertical cavity filter **15**, the thickness of the horizontal cavity filter **31** does not change vertically to the substrate surface. Thus, the fifth embodiment is much more compatible with normal semiconductor device processing in which a great number of devices are formed at a time on a single semiconductor wafer.

Embodiment 6

Hereinafter, a sixth embodiment of the present invention will be described with reference to FIGS. **7**A and **7**B.

FIGS. **7**A and **7**B illustrate cross-sectional structures, which are taken along the lines VIIA—VIIA and VIIB—VIIB in FIGS. **7**B and **7**A, respectively, of a demultiplexer according to the sixth embodiment. In FIGS. **7**A and **7**B, the same component as the counterpart illustrated in FIGS. **6**A and **6**B is identified by the same reference numeral. and the description thereof will be omitted herein.

In the demultiplexer of the sixth embodiment shown in FIGS. **7**A and **7**B, a horizontal cavity filter **31** is sandwiched between first and second photonic crystalline layers **23** and **24**. The first photonic crystalline layer **23** is formed between the substrate **30** and the filter **31** and the second photonic crystalline layer **24** is formed on the filter **31**. In addition, a third photonic crystalline layer **25** with the same function as that of the reflective block member **35** of the fifth embodiment is also formed between the first and second photonic crystalline layers **23** and **24**.

Each of the first, second and third photonic crystalline layers **23**, **24** and **25** is formed as a stack of a number of lattice layers. In each of the lattice layers, multiple dielectric (e.g., SiO_2) fine lines with a width of about 360 nm or multiple semiconductor (e.g., GaAs) fine lines with a width of about 170 nm are arranged to form a lattice. Each of the photonic crystalline layers **23**, **24** and **25** is a multilayer structure in which the locations of the fine lines in the n^th layer (or the $(n+1)^{th}$ layer) shift from those of the fine lines in the $(n+2)^{th}$ layer (or the $(n+3)^{th}$ layer) by a half period.

The first and second photonic crystalline layers **23** and **24** confine the incoming light beam **60** and reflected rays thereof within the horizontal cavity filter **31** so that the beam and rays will not diffuse vertically to the substrate **30**.

That is to say, the first and second photonic crystalline layers **23** and **24** are supposed to have a band structure corresponding to a photonic band gap covering the entire wavelength range of the incoming light beam **60**. In that case, the incoming light beam **60** cannot enter the first and second photonic crystalline layers **23** and **24** and therefore travel in parallel to the surface of the substrate **30**. As a result, the transmission loss of the horizontal cavity filter **31** can be reduced. The third photonic crystalline layer **25** should also have a band structure corresponding to a photonic band gap covering the entire wavelength range of the incoming light beam **60**. Then, the incoming light beam **60** can be reflected almost totally by a surface of the third photonic crystalline layer **25** that faces the horizontal cavity filter **31**.

What is claimed is:

1. A demultiplexer comprising:

a semiconductor substrate; and

a vertical cavity filter, which is formed on the principal surface of the substrate and transmits an incoming light beam with a predetermined wavelength,

wherein a resonant wavelength of the filter changes depending on at which point on the principal surface the light beam is incident, and

wherein the substrate has a recess with a slope that reflects or refracts the light beam and thereby makes the light beam incident onto the filter.

2. The demultiplexer of claim **1**, wherein the filter comprises:

a first distributed Bragg reflector, which is formed out of a first semiconductor layer on the principal surface of the substrate;

a spacer layer, which is formed out of a second semiconductor layer on the first reflector; and

a second distributed Bragg reflector, which is formed out of a third semiconductor layer on the spacer layer,

wherein at least one of the first, second and third semiconductor layers has its thickness changed relative to the principal surface of the substrate.

3. The demultiplexer of claim **1**, wherein the slope is a crystallographic plane that has been exposed by a wet etching process and has a predefined crystallographic plane orientation.

4. A demultiplexer comprising:

a semiconductor substrate; and

a photonic crystalline layer, which is formed on the principal surface of the substrate and transmits an incoming light beam with a predetermined wavelength,

wherein a wavelength at an edge of a photonic band of the photonic crystalline layer changes in a direction parallel to the principal surface of the substrate.

5. The demultiplexer of claim **4**, wherein the substrate has a recess with a slope that reflects or refracts the light beam and thereby makes the light beam incident onto the photonic crystalline layer.

6. The demultiplexer of claim **5**, wherein the photonic crystalline layer is made up of a plurality of dielectric or semiconductor fine lines that are arranged like a lattice, and

wherein the width of each said fine line or a gap between adjacent ones of the fine lines changes in a direction parallel to the principal surface of the substrate.

7. The demultiplexer of claim **4**, wherein the slope is a crystallographic plane that has been exposed by a wet etching process and has a predefined crystallographic plane orientation.

8. A demultiplexer comprising a horizontal cavity filter, the filter being formed on a substrate and transmitting a part of an incoming light beam traveling in a direction substantially parallel to the surface, the part transmitted having a predetermined wavelength,

wherein the filter includes:

a first distributed Bragg reflector, which is formed to make an optical path of the light beam parallel to the surface of the substrate; and

a second distributed Bragg reflector, which is formed to be spaced apart from the first reflector.

9. The demultiplexer of claim **8**, wherein each of the first and second distributed Bragg reflectors is formed by arranging a plurality of dielectric or semiconductor thin plate members on the substrate at regular intervals so that the plate members cross the optical path.

10. The demultiplexer of claim **8**, wherein a resonant wavelength of the filter changes depending on at which point on the substrate the light beam is incident.

11. The demultiplexer of claim **10**, wherein the space between the first and second distributed Bragg reflectors changes and is tapered or stepped in the direction parallel to the surface of the substrate.

12. The demultiplexer of claim **8**, further comprising:

a first photonic crystalline layer, which is formed between the substrate and the filter; and

a second photonic crystalline layer, which is formed on the filter.

13. The demultiplexer of claim **12**, wherein each of the first and second photonic crystalline layers is made up of a plurality of dielectric or semiconductor fine lines that are arranged like a lattice.

14. A demultiplexer-receiver comprising:

a semiconductor substrate;

a vertical cavity filter, which is formed on the principal surface of the substrate and transmits an incoming light beam with a predetermined wavelength; and

a plurality of light-receiving areas defined on the filter,

wherein a resonant wavelength of the filter changes depending on at which point on the principal surface the light beam is incident, and

wherein the substrate has a recess with a slope that reflects or refracts the light beam and thereby makes the light beam incident onto the filter.

15. The demultiplexer-receiver of claim **14**, further comprising a light-absorbing layer and a window layer that are formed in this order on the filter,

wherein the window layer includes a plurality of doped regions that are defined like islands, and

wherein the light-receiving areas are respective parts of the light-absorbing layer that are located under the doped regions.

16. A demultiplexer-receiver comprising:

a semiconductor substrate;

a photonic crystalline layer, which is formed on the principal surface of the substrate and transmits an incoming light beam with a predetermined wavelength; and

a plurality of light-receiving areas defined on the photonic crystalline layer,

wherein the substrate has a recess with a slope that reflects or refracts the light beam and thereby makes the light beam incident onto the photonic crystalline layer.

17. The demultiplexer-receiver of claim **16**, further comprising a light-absorbing layer and a window layer that are formed in this order on the photonic crystalline layer,

wherein the window layer includes a plurality of doped regions that are defined like islands, and

wherein the light-receiving areas are respective parts of the light-absorbing layer that are located under the doped regions.

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